CHAPTER 19

Electrical Nerve Stimulation
for Regional Anesthesia

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INTRODUCTION

Electrical stimulation is the most commonly used method to localize nerves before the injection of a local anesthetic in performing regional anesthesia. The electrical nerve stimulator (ENS) produces an electrical current that depolarizes the nerve membrane and causes contraction of the effector muscles or sensory stimulation of the relevant area. This confirms the proximity of a needle to the nerve. To use the ENS effectively, a basic understanding of the electrophysiologic principles involved is necessary.

HISTORICAL BACKGROUND

Although electrical stimulation gained wide acceptance in regional anesthesia only over the last two decades, this technique was first described by von Perthes in 1912. Beginning in 1955, a number of researchers further improved it. Pearson described the localization of nerves with motor responses by electrical stimulation with an insulated needle, Greenblatt and Denson described the use of a portable transistorized nerve stimulator with pulsed variable output, and Montgomery et al. demonstrated that ordinary uninsulated needles could be used, albeit with a higher current. Finally, in 1980, Ford, Pither, and Raj emphasized the important characteristics of the ENS and described the performances of insulated and uninsulated needles.

ELECTROPHYSIOLOGY
OF NERVE STIMULATION

The ENS excites nerves by producing an electrical current that induces a flow of ions through the nerve membrane and initiates an action potential (Fig. 19-1). The characteristics of the electrical impulse affect its ability to stimulate nerve fibers. In addition, the distance from the nerve, polarity, and type of the electrode used also greatly influence the quality of stimulation.

Effects of the Characteristics of Impulse

Intensity

When a square pulse of current is applied to a nerve, a charge \( Q \) is delivered that is equal to the product of the intensity \( I \) of the applied current and the duration \( t \) of the current pulse:

\[
Q = I \times t
\]

When intensity is plotted against duration, a typical stimulation or excitability curve is obtained, with the relationship \( I = I_r (1 + C/t) \), with two important parameters:

1. The rheobase \( I_r \), which is the minimum current intensity, required to stimulate the nerve
2. The chronaxy \( C \), which is the minimum duration of the pulse required to stimulate the nerve when the intensity of the current is twice the rheobase
The rheobase and chronaxy demonstrate that it is not possible to stimulate a nerve by applying a current below a threshold intensity, regardless of the pulse duration, nor by applying a current below a threshold duration, regardless of its intensity.7

It has been observed that the larger the fiber, the easier it is to stimulate it and the shorter its chronaxy.9 Different types of nerve fibers can be stimulated by varying the electrical pulse widths. Large A-alpha motor fibers with chronaxies of 50 to 100 µs can be stimulated without stimulating the smaller A-delta and C fibers (responsible for pain transmission), with chronaxies of about 150 and 400 µs, respectively.9,10 By using a minimal current and a short pulse, a twitch of the muscles supplied by the motor fibers can be produced without causing pain, since the sensory fibers need a longer pulse for stimulation. However, more recent data suggest that the duration of the pulse is not important in causing pain or discomfort during electrostimulation.11,12 The main causes of discomfort seem to be related to the withdrawal and repositioning of the stimulating needle;13 the strength of the elicited muscle contraction, and high intensities of the stimulating current.11

A short pulse can be used as a sensitive indicator of the distance between needle and nerve.5 When the needle tip is touching the nerve, the duration of the stimulating current has only a moderate effect on the minimal intensity required. However, when the needle tip is remote from the nerve, the pulse duration becomes very important. When the tip of the needle is 1 cm away from the nerve, instead of touching it, a tenfold increase in the current is required with a 40-µs pulse to cause stimulation. If the pulse is lengthened to 1 ms, the necessary increase in current is only twofold.

Rate of Change
Finally, it may not be possible to stimulate a nerve fiber no matter how strong the stimulus if it is applied too slowly. A prolonged subthreshold stimulus or a slowly rising current may reduce nerve excitability by inactivating sodium conductance before the depolarization reaches the threshold.14 This is known as “accommodation” of nerve fibers. To avoid accommodation, square waves of current are used to keep the rising time very short.

Relationship between Current Intensity and Distance from the Nerve
The closer the stimulating electrode is to a nerve, the lower the current intensity necessary for its excitation, as stated in Coulomb’s law:

\[ I = k \left( \frac{i}{r^2} \right) \]

where \( I \) is the current required, \( k \) is a constant, \( i \) is the minimal current, and \( r \) is the distance from the nerve.

Since the relationship is the inverse of the square of the distance, a very high current is needed when the electrode is far from the nerve, and much less is needed as the electrode comes closer to the nerve. It is calculated that the current intensity necessary to stimulate a nerve is 0.1 mA when the electrode is right on the nerve, 2.5 mA when the electrode is 0.5 cm away from the nerve, and 40 mA when the electrode is 2 cm away.10 In the clinical context, these higher currents may be sufficient to cause microshock if they are applied directly to the heart and become painful by directly stimulating nerve endings in the surrounding tissues.

Preferential Cathodal Stimulation
If two electrodes are placed on a nerve and a direct electrical current is made to flow through them, the nerve fiber is stimulated at the cathode (negative electrode) and becomes more resistant to excitation at the anode (positive electrode) (Fig. 19-1).15 The negative current from the cathode reduces the voltage immediately outside the
membrane. Consequently, the voltage difference across the membrane is decreased, causing an area of depolarization and an action potential. Conversely, at the anode, the injection of positive charges outside the nerve membrane increases the voltage difference across the membrane, causing hyperpolarization and a decrease in excitability (Fig. 19-1). Cessation of an anodal current may, however, overshoot the membrane potential in the depolarizing direction. This rebound may be large enough to initiate an action potential. If the anode instead of the cathode is used as the stimulating electrode to elicit a motor response, three to four times more current is required.5,11,16

Types of Electrodes/Needles
The needle is an extension of the stimulating electrode. Two types of stimulating needles can be used for this purpose: (1) electrically insulated or (2) uninsulated. Their properties and the geometries of the electrical fields they produce are quite different (Fig. 19-2).6,17,18

Insulated Needles
The shafts of insulated needles are covered with a layer of nonconducting material (e.g., Teflon), leaving the tip bare. On stimulation, the pattern of the current density is a sphere around the tip of the needle (Fig. 19-2). Because of the small conducting area, there is a high current density at this point, and a low threshold current is sufficient to localize the nerve. Insulated needles with a cutting bevel are normally used. This type of needle requires a threshold current of about 0.5 to 0.7 mA and a pulse width of 100 µs to stimulate a nerve when it is approximately 2 to 5 mm away. More sophisticated needles have a pinpoint electrode tip, where both the shaft and the bevel are insulated and only the very tip of the needle can conduct the current.19 The pinpoint electrode concentrates the entire stimulus current in this very small area, allowing for even more precise localization of the nerve with very low threshold currents, such as only 0.2 mA with a 100-µs pulse.

Uninsulated Needles
Uninsulated needles transmit the current throughout their entire length (Fig. 19-2). These needles require higher minimal currents than insulated ones, generally in excess of 1 mA, to excite a nerve.17 The maximum current density is at the needle tip with a zone extending up the needle shaft. With these needles, it is more difficult to localize the nerve accurately with low current intensities. As the needle tip moves further past the nerve, the required current remains constant because of continuous stimulation by the shaft.6 Thus, “false localization” may occur due to stimulation of the nerve by the shaft instead of the tip of the needle.

> THE MODERN ELECTRICAL NERVE STIMULATOR

The electrical characteristics of the ENS that contribute to the successful localization of a peripheral nerve include the following.5,20

Constant and Linear Current Output
With the newer type of ENS, the current output may be set in milliamperes (intensity) or in nanocoulombs (charge). The relationship \( nC = mA \times \mu s \) is obtained from \( Q = I \times t \). (For example, a 2-mA current applied for 50 µs provides a 100-nC charge; the same current applied for 300 µs provides a 600-nC charge.) Ideally, the current output of the ENS (intensity or charge) should remain unaffected by changes in the resistance of the entire circuit, such as those arising from tissue, needles, connectors, etc., and should also remain constant throughout a wide range of resistances. In the past, most commercially produced nerve stimulators utilized a constant voltage system. However, since it is the current and not the voltage that stimulates the nerve,
new models now deliver a constant current in spite of changes in resistance. A linear current output, especially in the lower range, is also an important feature of the ENS. With a nonlinear output, a small movement of the dial in setting the current strength may result in a large change in intensity. A nerve stimulator with low- and high-output ranges will often have a linear output in the low range (0 to 5 mA) and a logarithmic output in the high range of intensities (as when it is used to monitor neuromuscular blockade). Current delivery, especially in the low-intensity range, was variable with older ENS models, but newer models with constant and linear output circuitry deliver current with greater accuracy.

Variable Pulse Width

The duration of the delivered electrical pulse is an important element in neurostimulation because, apart from determining the amount of charge delivered, pulse width plays a role in the selectivity and precision of stimulation, as described earlier. Most nerve stimulators deliver an electrical pulse width of 100 or 200 µs for stimulating motor nerves as their default settings. However, more sophisticated devices can provide variable pulse widths from 50 to 1 ms.

Clearly Marked Polarity of the Electrodes

With the newer types of ENS, the cathode has a specialized male connector designed to fit into the female conducting portion of the stimulating needle. This serves two purposes: it avoids confusion between the electrodes and provides greater safety by eliminating any exposed “live” connection. The cathode should preferably be the stimulating electrode, as it is three to four times more effective than the anode in producing depolarization of the nerve membrane.

Variable Pulse Frequency

With newer ENS models, the frequency of the delivered electrical pulse can be changed. The optimal is between 0.5 and 4 Hz, and most users select a frequency of 1 or 2 Hz.

PRACTICAL CONSIDERATIONS OF PERIPHERAL NERVE BLOCKS

Previously, it was thought that, to prevent direct stimulation of muscles via local flow of the current, the returning electrode (which should be the anode or positive electrode) had to be positioned on the patient’s skin at least 20 cm away from the site of stimulation. However, new data suggest that the site is not critical. With a constant-current-output ENS, changing the position of the returning electrode from a remote location to 5 cm away from the stimulation site did not result in any change in the grade of the motor response or in the current required to maintain it. The stimulating needle is connected to the cathode and the area where the needle is to be inserted is disinfected. The needle is advanced through the skin and the stimulator is turned on at the relatively high intensity of 2 to 3 mA, with a pulse of 100 to 200 µs. Under these conditions, an electrical charge large enough to excite the nerve is delivered while the needle is still at some distance from it without causing discomfort to the patient. Once contractions of the appropriate muscle group are elicited, the needle tip is likely to be 1 to 2 cm away from the nerve. The needle is advanced further and, if the strength of the twitches increases, the current intensity is decreased. The current is gradually reduced until the smallest response is observed. The needle is moved until a muscle twitch is visible with a minimal current, usually around 0.5 mA. Until recently, there were no available data regarding the optimal current necessary to localize nerves. It has been postulated that stimulation at currents higher than 0.5 mA may result in block failure because the needle tip is too far from the nerve, while stimulation at currents lower than 0.2 mA may possibly increase the risk of intraneural injection. In a recent study, Hadzic et al. showed that the minimal current necessary to produce a clearly visible twitch, without movement of the extremity, was about 0.3 mA with a 100-µs duration. They suggested that it was unnecessary to search for a nerve response at currents lower than 0.2 mA (100 µs), since, under these conditions, all their blocks (femoral and interscalene) were successful with a small volume of local anesthetic. These values may not apply to the placement of perineural catheters.

In diabetic and elderly patients, some nerves may have a higher threshold, and it may be necessary to start with a higher current. After aspirating to check that the needle tip is not in a blood vessel, a test dose of 1 to 2 mL of local anesthetic is injected. If the needle is position correctly, the muscle twitch should disappear almost immediately. This phenomenon, commonly known as the “Raj test,” can also be demonstrated by injecting similarly small volumes of saline or air. Previously, the disappearance of the muscle twitch was attributed to the physical displacement of the nerve from the stimulating needle tip by the injected fluid. However, Tsui et al. recently demonstrated that this phenomenon is best explained in electrical terms and is not entirely due to displacement of the nerve. Only after successful aspiration and injection tests is the full dose of local anesthetic slowly administered.

In stimulating purely sensory nerves, the position of the needle tip near the nerve is confirmed when the
patient reports a radiating paresthesia with every pulse in the distribution of the nerve. The sensation should be felt at low current as for a motor block but preferably using a longer, 300-µs to 1-ms pulse width.10,28

NEW ASPECTS OF ELECTRICAL STIMULATION

Peripheral Nerve Block

New Understanding of Nerve Stimulation

As described above, a small volume of local anesthetic or normal saline abolishes the muscle twitch induced by a low current (0.5 mA) during nerve stimulation. Despite years of clinical use of nerve stimulation in regional anesthesia, the electrophysiologic effect of such injections on nerve conduction has remained unexplained until recently. In a porcine model, Tsui et al. demonstrated that the injection of 0.9% NaCl abolished the motor response, while a subsequent injection of 5% dextrose in water (D5W) reestablished effective stimulation.27 An accompanying in vitro experiment showed that injections of solutions such as 0.9% NaCl or 5% D5W cause a change in the electrical field at the needle-tissue interface (Fig. 19-3). It was concluded that the injection of electrically conducting solutions (saline or local anesthetic) increases the conductive area surrounding the stimulating needle tip. This causes a decrease in the current density surrounding a target nerve, which is therefore no longer stimulated. This suggests that effective nerve stimulation is sensitive to changes that occur at the needle-tissue interface, such as a change in the angle of the needle or injection of local anesthetic. The net effect appears to be a change in the current density at the tip of the needle or the path of the electric current, which affects the motor response.20

In view of these studies, further work will be needed to establish a new, acceptable current range for motor responses after dilating the perineural spaces with conducting solutions as commonly performed for the placement of perineural catheters. It is not certain, however, whether this “dilating of the perineural spaces” in fact does actually take place. On the other hand, one may use a nonconducting solution, such as D5W, instead of saline, for dilating perineural spaces.27 Future studies are also warranted to determine the merit of using nonconducting injections in peripheral nerve blocks.

Percutaneous Electrode Guidance (PEG) and “Nerve Mapping”

In recent years, percutaneous location of nerves via transcutaneous stimulation has been used to identify the optimal point on the skin for insertion of the block needle. Several types of cutaneous stimulating electrodes have been tried. These include a modified (0.5-cm diameter) electrocardiograph electrode,25 the negative electrode of the nerve stimulator,28,29 and a stub needle.30–32 A cylindrical electrode with a 0.5-mm metallic tip has also been used successfully to guide the block needle via a central 22-gauge hole.32 Recently, the tip of the actual stimulating needle has been used directly.33 The smaller the electrode, the greater the current density applied to the skin and the greater the effect on the tissue.

Capdevila et al. described PEG using the same needle for both prelocation and nerve blockade.33 The tip of the needle is gently pressed on the patient’s skin surface and moved around until a motor response is obtained by using an initial transcutaneous current of 5 mA with a 200-µs pulse width. The stimulating current is then reduced to the minimum intensity required to produce a visible motor response. When the optimal location of the nerve is identified, the needle is inserted at 90 degrees through the skin and a 2-mA current of 100-µs duration is applied. As the required motor response is elicited, the needle depth is adjusted and the current intensity decreased until the muscle twitches are still visible at 0.5 mA. The median value of the minimal transcutaneous current needed to stimulate the nerves of the axillary brachial plexus is 2 to 3 mA. This method of percutaneous electrode guidance is said to be simple, reliable, noninvasive, and painless.

CENTRAL NEURAXIAL BLOCKS

Electrostimulation is now well accepted for identifying peripheral nerves in performing regional anesthesia.26 In recent years, the same technique has been applied to
central neuraxial blocks and has been shown to be a safe, reliable, and easy-to-use method to monitor and confirm correct placement of epidural catheters. Although both aspiration of the epidural catheter and standard test doses (e.g., 3 mL of 1.5% lidocaine with 1:200,000 epinephrine) can detect misplaced subarachnoid or intravascular catheters, many examples of false-positive and false-negative results are associated with these tests. In addition, verification of proper epidural catheter placement is not possible with either of these techniques. Previously, it was thought that radiologic imaging was the only way to confirm that a catheter was located in the epidural space prior to local anesthetic injection. However, recent advances in epidural anesthesia have demonstrated that electrical stimulation (the Tsui test) may be a reliable technique for this purpose.

**ADVANTAGES OF NEUROSTIMULATION: DOES IT MAKE A DIFFERENCE?**

Intuitively, a greater success rate and enhanced safety of the blocks should be expected with ENS. Compared with other methods of nerve localization, such as paresthesia, there is no need to rely on the patient’s reports in localizing motor or mixed nerves, and the more accurate placement of the needle should decrease the risk of intraneural injections. In spite of these considerations, earlier clinical studies have claimed that the success rate of blocks performed with neurostimulation was not increased. However, the ENS was found to be superior to a radiographic technique in blocking the obturator nerve. Sciatic nerve blocks performed with the ENS were also shown to have a greater success rate than with the paresthesia technique. For axillary blockade of the brachial plexus, when only a single nerve is stimulated, the success rate appears to be similar to that of the more traditional transarterial or paresthesia techniques. This is not the case, however, when multiple nerves are stimulated. Greater chances of successful block and shorter onset times are reported with multistimulation. In conjunction with a good loss of resistance technique, careful aspiration, and the use of a test dose, the ENS should improve the safety and success rate of epidural anesthesia.

**REFERENCES**